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Abstract Title: Clinical Implementation of Monte Carlo-based Dose and Linear Energy Transfer Calculations in Carbon-ion Radiotherapy: Multi-site Comparison with Treatment Planning System

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Aims:

- This study aims to evaluate the clinical feasibility of Monte Carlo (MC)-based dose and dose-averaged linear energy transfer (LET_d) calculations in carbon-ion radiotherapy (CIRT) across multiple tumor sites.

Methods:

- In this study, we developed and validated an in-house TOPAS-based MC system for CIRT, capable of calculating biological dose and LET_d distributions. The system implements the modified microdosimetric kinetic model (mMKM). LET_d distributions were calculated for ions (Z≥1) using the *G4EmCalculator class*.

- For validation, the developed system was used to recalculate treatment plans for prostate, lung and liver cancer cases. A comparative analysis was performed between the MC and treatment planning system (TPS) results. Dose distributions were evaluated using gamma analysis (2%/2mm) and dose volume histograms (DVHs), while LET_d distributions were assessed with LET volume histograms (LETVHs) for the target and organs-at-risk (OARs).

Result:

- In the prostate cancer case, dose distributions calculated by MC simulations showed high agreement with TPS results, with gamma passing rates exceeding 97.0%. The relative error in target LET_{mean} was 0.4%, while the LET_{mean} differences for the bladder and rectum were 13.5% and 28.0%, respectively.

- In the lung cancer case (Figure 1), gamma passing rates were 98.4%, indicating consistent dose agreement despite anatomical heterogeneity. The LET_{mean} in the target region differed by 1.2%, and heart and left bronchus exhibited deviations of 8.8% and 16.8%, respectively.

- For the liver cancer case, the gamma analysis confirmed a high degree of dosimetric accuracy with passing rates consistently above 97.5%. This precision extended to the biological calculations, as the LET_{mean} difference in the target was only 2.1% and the gallbladder showed a similarly low deviation of 3.1%.

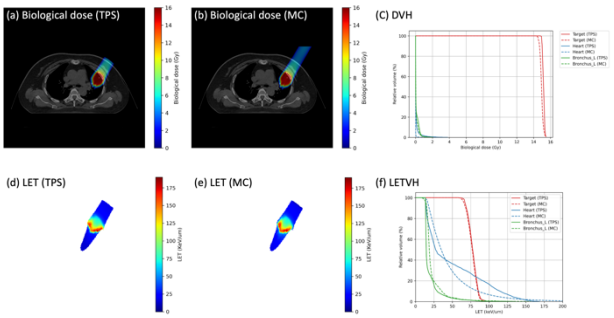

Figure 1. Comparison of biological dose and LET distributions between the treatment planning system (TPS) and Monte Carlo (MC) simulation for a lung cancer case.